

Theoretical/Experimental Characteristics of Interosseous Membrane of Human Forearm

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Abstract- The interosseous membrane (IOM) is a fibrous structure located within the forearm that possesses distinct direction and shape patterns. The membrane maintains the interosseous space between the radius and ulna through forearm rotations and actively transfers forces from the radius to the ulna. The interosseous membrane's load transferring ability reduces the forces placed on the radiocapitellar joint, thereby preventing radial head fracture. However, large chronic loading results in attenuation of the membrane fibers, thereby reducing longitudinal stability. We propose that the IOM functions similarly to a composite material composed of stiff central fibers (longitudinal portion) surrounded by a supporting fibrous matrix (transverse portion). A novel theoretical/experimental approach is taken to measure mechanical properties of the intact interosseous membrane. This data will be necessary for modeling forearm stability in normal and pathologic conditions and analysis of repair procedures.

Keywords- Interosseous Membrane, biomechanical properties, composite materials

I. INTRODUCTION

In the development of the forearm biomechanics, the forces generated during the gripping process must be determined. Models have been proposed as to the kinematic movements of the tendons in the hand, as well as the force transmissions through the wrist [1]. The total load measured at the radius and ulna has been shown in one study [2] to be 78% and 22% respectively and in another [3] to be 81.6% and 18.4% respectively. A number of articles are available focusing on characterization of the IOM in force transmission. Rabinowitz et al. [4] demonstrated that the IOM adds to the stability of the forearm and partakes in the transfer of force from radius to the ulna. In particular, the authors showed that the portion of the IOM most responsible for stability is the center 1/3 section of the membrane. Hotchkiss et al [5] used load cells and a stiffness-testing machine to confirm the strength portion of the IOM. The results of their tests showed not only were the central band of the IOM the strongest, but it was also the thickest. Furthermore, they showed that the additional thickness of the central band of the IOM contributes to its overall increased stiffness properties. The results of their tests

provided valuable information about the key role the IOM plays in the mechanical physiology of the forearm. Their results were compared to this paper's results, obtained through material testing of IOM fibers, as well as testing of the individual sections.

II. COMPOSITE MATERIAL THEORY

The basic rods-in-matrix model is based on a long-fiber reinforced polymer construction. The main feature of a composite is its in-plane stiffness in the principle directions. The purpose of the fibers in the material is to stiffen and strengthen the composite. This rod-in-matrix structure leads to the definition of two moduli under uniaxial stress. One modulus is defined along the fibers (E_1), and the other modulus is defined across the fibers (E_2). The longitudinal modulus E_1 of the unidirectional lamina is related to the properties of matrix E_p and fiber E_f , and the volume fraction of fibers, V_f , by the rule of mixtures:

$$E_1 = V_f E_f + E_p (1 - V_f) \approx V_f E_f \quad \text{where } E_p \ll E_f \quad (1)$$

Therefore, the greater the volume fraction of the fibers, the larger the longitudinal modulus, E_1 . The rule of mixtures also applies to the Poisson's ratio ν_{12} :

$$\nu_{12} = V_f \nu_f + V_p (1 - \nu_f) \quad (2)$$

The strength of the unidirectional lamina in the principle directions is derived based on the assumption that the fibers are all of the same length and strength. A dissecting microscope at 40X magnification showed the microstructure of the specimen (Figure 1). The fibers tended to be oriented in a longitudinal direction, originating at the radius and projecting distally to the ulna. Furthermore, there was no crossply pattern in the membrane, suggesting a model of a single ply with the fibers oriented in the same direction.

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Figure 1: 40X IOM Microstructure

Based on microstructural similarities between ligaments and the IOM, a macromechanical model of the IOM was developed that utilizes the characteristics of a single-ply composite with all fibers oriented in the same direction. Furthermore, based again on the IOM's similarities to ligaments, the properties of the IOM were assumed to possess a high proportion of elastin fibers surrounded by a collagen matrix. Lastly, the composite was assumed to be orthotropic due to the organization of the IOM's microstructure. Therefore, the material properties were calculated as:

V_f – Volume fraction of fibers

V_m – Volume fraction of matrix

E_f – Modulus of fibers

E_m – Modulus of matrix.

Longitudinal Modulus: $E_1 = E_f V_f + E_m V_m$

Transverse Modulus: $1/E_2 = V_f/E_f + V_m/E_m$

Known Data [6]

$V_f = 65\%$, $V_m = 35\%$, $E_f = 0.3 \text{ MPa}$, $E_m = 100 \text{ MPa}$

Therefore, Longitudinal Modulus:

$$E_1 = E_f V_f + E_m V_m = (0.3 \cdot 0.65) + (100 \cdot 0.35) = 35.20 \text{ Mpa}$$

Transverse Modulus:

$$1/E_2 = V_f/E_f + V_m/E_m = 0.65/0.3 + 0.35/100 = 2.17$$

$$E_2 = 0.46 \text{ Mpa}$$

Thickness measurement

The system was first calibrated using standard weights and measurements. The dissected sample was removed from cold storage and mounted in the longitudinal tensile testing clamps.

The distal and proximal portions of the radius and ulna were stabilized to maximize the IOM surface area available for measurement. A SK-031 laser system and RD controller (Keyence Corporation, Saddlebrook, NJ) were positioned on both sides of the IOM. The laser system was moved over the length of the membrane at one-eighth inch intervals providing a complete mapping of the IOM's central thickness. The resolution of the laser system was quoted at 1 micron with a measurement range of $\pm 5 \text{ mm}$. Using data acquisition software, the data were analyzed to provide an accurate representation of the thickness distribution within the sample. The sample was then removed from the clamping apparatus and prepared for tensile testing. The samples were placed into the clamping device and attached to the tensile testing apparatus. Figure 3 demonstrates the assembled system for testing the transverse properties of the IOM.



Figure 2: IOM Testing Setup.

For shear testing, a two-inch long sample of the central third of the IOM was isolated by removal of the proximal and distal portions of the radius and ulna. Enough bone was maintained to permit mounting onto the longitudinal clamping structure (Figure 3).

The specimens were clamped at the radius and ulna, centering the central IOM band in the long axis of the tensile testing apparatus and in a supinated position to allow for the determination of material properties without influence of rotational orientation. The sample width was measured prior to tensile testing with a digital micrometer.

Following measurements for thickness and width, the DAS-16G1 data acquisition system was connected to the load cell and the internal elongation sensor. The load cell and elongation sensor monitor the force applied to the sample and the elongation at each time point. The data acquisition system was programmed to obtain data from two channels with a differential input at $\pm 1 \text{ V}$. The sampling rate of the system was set at 50 hertz for 200 seconds. The rate of elongation was adjusted to 12.7 mm/min (0.5 in/min) to provide a slow "quasi-equilibrium" state of force application. A scale of 50% maximum for force and 0.127 m (5 in) maximum for

elongation was used to maximize the range and accuracy of the system.

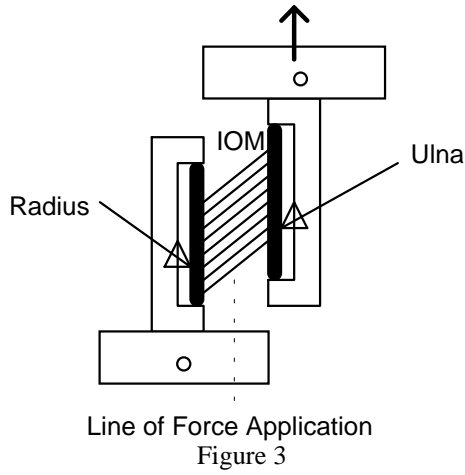


Table 1: Results of the Shear Tensile Testing of the Interosseous Membrane.

#	Race/Sex/ Hand	Age (yr)	Max Force (N)	Max F/w (N/m)	Max σ (MPa)	Elastic Mod. (MPa)
1	WF – Left	67	1231.16	33274	23.19	202.0
2	WF – Right	67	1118.86	25428	18.14	177.5
3	WM – Left	69	1088.26	23154	16.54	202.0
4	WM – Right	69	967.23	19344	11.07	129.3
5	WF – Left	71	1077.10	24479	17.06	165.2
6	WF – Right	71	1067.61	21352	13.35	121.2
7	WM – Left	73	1552.01	33021	17.18	114.0
8	WF – Left	77	756.31	16806	7.76	111.1
9	WF – Right	77	1034.27	19153	9.49	82.0
10	WM – Left	86	1140.07	21510	8.10	86.7
11	WM – Right	86	1081.05	26367	11.87	97.4
	AVERAGE	73.9	1101.27	23990	13.98	135.3
	STD.DEV.	6.88	5348.92	5348	4.85	41.6

III. RESULTS

The donor demographics and results of the shear testing are summarized in Table 1. The average age of the donor sample was 73.9 ± 6.9 years (avg. \pm std. dev.) with a range of 67 to 86 years. Six samples were obtained from female donors and five from male donors. The geometric measurements of the unstressed sample resulted in an average width of 46.5 ± 5.1 mm, an average thickness of 1.82 ± 0.42 mm and an average initial sample length of 38.7 ± 2.7 mm. The average maximum force produced at fiber fracture was $1,101 \pm 191$ N. Using the width measurement, the calculated average maximum force/width was $23,990 \pm 5,348$ N/m. The cross-sectional area of the central portion of the IOM was then calculated by using the thickness and width data of each sample equaling 85.4 ± 25.2 mm².

The plot of stress versus strain for each sample demonstrated a bi-phasic failure response. A representative graph of stress versus strain is shown in Figure 4. An initial peak in strength occurred due to the failure of the accessory membrane fibers, while the second, larger peak represented the failure of the main central IOM fiber. From the data, the initial failure strength of the accessory fibers was 4.98 ± 1.85 MPa with an elastic modulus of 93.67 ± 26.54 MPa. The number of accessory fibers varied from one to four and had no effect on the initial failure peak or the initial elastic modulus. The second peak in stress (main fiber failure) represented the ultimate strength of the IOM, which was found to equal 13.98 ± 4.85 MPa. Using linear regression, the average elastic modulus of the main fiber equaled 135.29 ± 41.57 MPa.

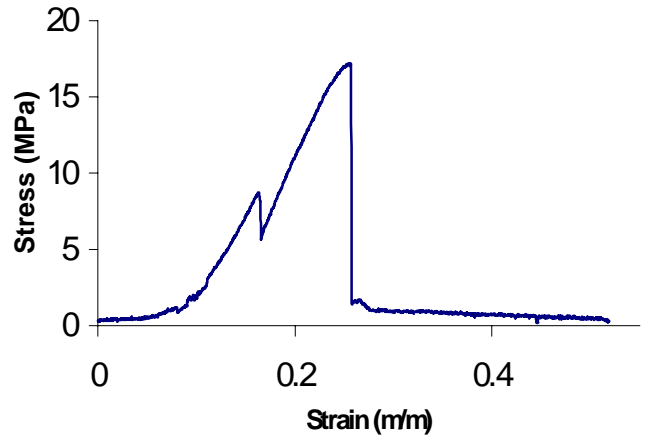


Figure 4: Typical stress vs. strain curve demonstrating the two peaks in fiber failure (accessory bundles and main bundle respectively) with similar elastic moduli (Arm #7).

Analysis of the results demonstrated an age variation in the elastic modulus of the main fiber as well as in the average sample thickness (Figures 5). The elastic modulus of each specimen was plotted versus age and a linear regression of the

data demonstrated a decrease in fiber stiffness of 4.78 MPa per year of age with a determination coefficient (R^2) of 0.63 (correlation coefficient: $r = 0.79$). A decrease in elastic modulus represents an increased compliance, or pliability of the sample. A similar plot of the elastic moduli of the accessory fibers showed no age related changes. A more significant correlation was found between sample age and sample thickness. The average sample thickness increased by 0.056 mm per year of age with a determination coefficient of 0.84 (correlation coefficient: $r = 0.92$). The age relation of elasticity may be due to changes in collagen type and organization.

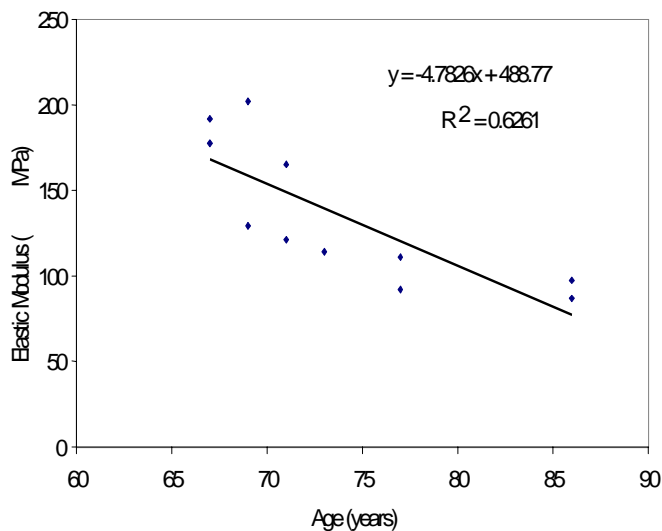


Figure 5: The groups of specimens tested demonstrated a decreased in elastic modulus with age.

The current treatment option for an irreparable radial head fracture is controversial with no classification that considers the incidence or severity of membrane damage. Once the severity of IOM damage is assessed, the proper repair procedure should be based on scientific findings of IOM function and behavior. Our findings provide a basis for understanding IOM mechanical properties and how they relate to patient age and forearm function. The testing model used in our study represents a novel approach to simulate force transfer within the central third of the IOM. It is also discovered that the IOM functions similarly to a single-ply lamina composed of a transverse matrix and main longitudinal fibers. The matrix component provides structural support and concentrates the forces on the main longitudinal load bearing fibers. By using the central third of the IOM, our testing procedure demonstrated the integration of the accessory membrane fibers with the function of the main fiber in force transfer and stability. Also, by preserving the bony attachments, the orientation of the fibers was maintained resulting in the failure of the accessory fibers first followed by failure of the main fiber.

The data on the elastic modulus of the main IOM fiber demonstrated a decrease with age in the samples tested (Figure 5). The change in elasticity may be due to changing collagen structure or type, changes in ultrastructural fiber number, or changes in collagen crosslink density. Membrane stiffness variations based on age may influence the mechanics of the forearm after injury especially after radial head resection. Older patients with more elastic membranes may demonstrate increased proximal migration of the radius under lower loads than younger patients with stiffer membranes.

By placing the IOM in a controlled shearing state, our experimental model produced an approximate representation of the force transfer from the radius to the ulna. Our testing apparatus simulates the fatigue forces generated when the IOM is subject to increased chronic loading. The IOM's in-vitro response data to these chronic shearing forces was used to calculate the mechanical properties (ultimate strength and elastic modulus) of the membrane fibers. The mechanical properties of the IOM provide the basis upon which the physiology of the structure can be defined. This data will later be used for computer simulation of the load transfer using finite element methods. From a clinical perspective, our data can be used for future development of IOM grafts and repair procedures and possibly material replacement.

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